



LOW-LOSS FREQUENCY SELECTIVE SURFACES ON SILICON SUBSTRATES FOR SUB-MILLIMETER WAVE APPLICATIONS

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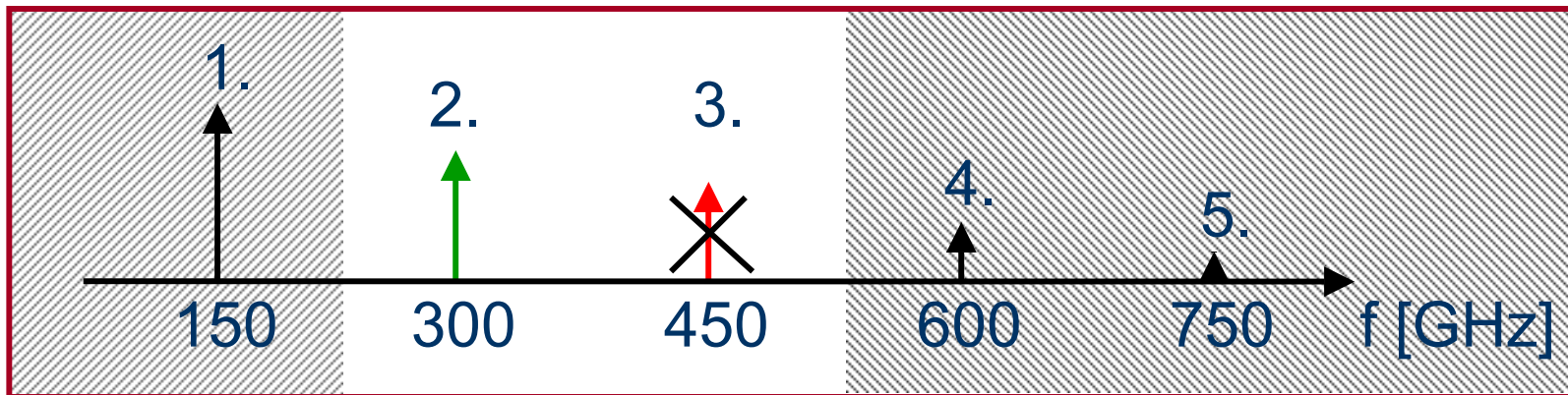
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MOTIVATION OF THE WORK



Quasi-optical filters for suppressing harmonic frequencies from solid-state frequency multiplier.

EXAMPLE: frequency doubler pumped at 150GHz.



cut-off of
waveguide

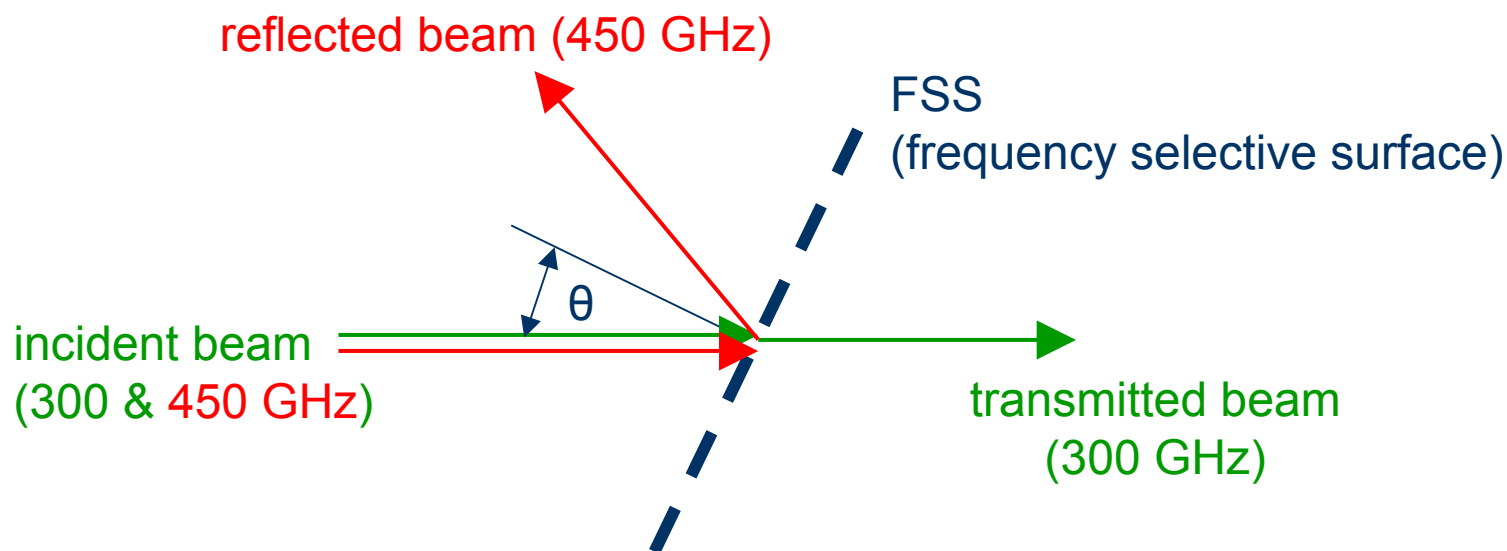
very low output power of
semiconductor sources



DESIGN GOALS / 1

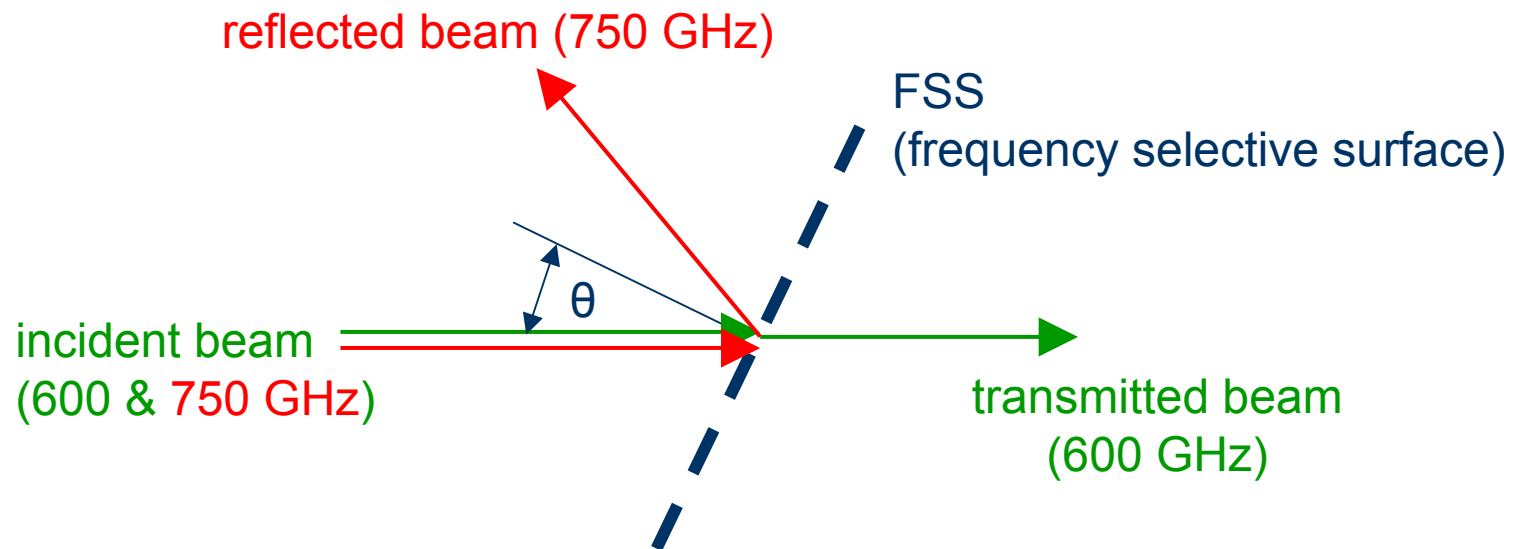
FILTER 1

- pass band @ 300GHz, insertion loss < 2dB
- stop band @ 450GHz, insertion loss > 20dB



FILTER 2

- pass band @ 600GHz, insertion loss < 2dB
- stop band @ 750GHz, insertion loss > 20dB



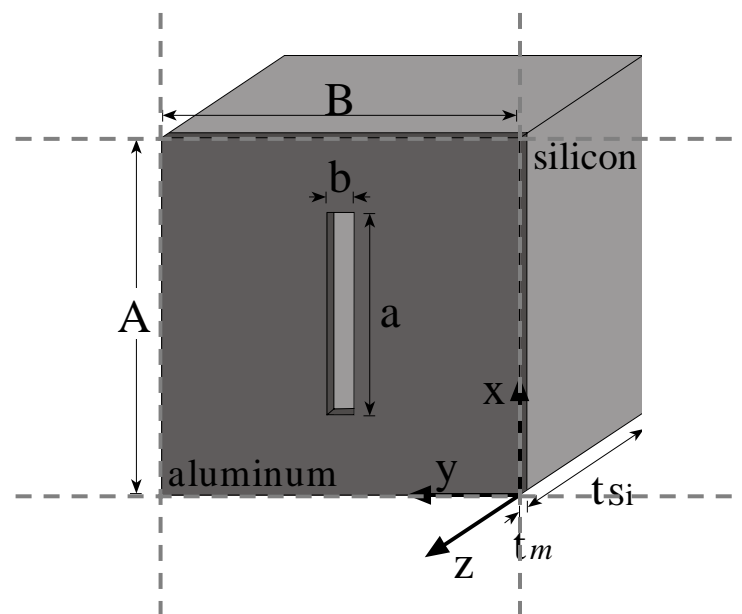
Additional requirements:

- mechanically robust
- standard semiconductor manufacturing technologies



FSS CONFIGURATION

Thin metal screen backed by a thick silicon substrate. Rectangular slots are preliminary considered.



DESIGN PARAMETERS

- aluminum layer thickness $t_m = 2\mu\text{m}$
 - incidence angle: initial design for $\theta = 20^\circ$
 - thickness of silicon wafer (t_{Si})
 - length of the rectangular slot (a)
 - size of unit cell (A and B)
- chosen "a priori"
- to be optimized



TENTATIVE PARAMETER VALUES

1. The **substrate thickness** t_{Si} must satisfy the Fabry-Perot resonance condition at f_{pass}

$$t_{Si} = k \cdot \frac{c}{2f_{pass}\sqrt{\epsilon_r}} \cdot \cos \left[\arcsin \left(\frac{1}{\sqrt{\epsilon_r}} \sin \vartheta \right) \right]$$

2. The **slot (with length a)** must be resonant at f_{pass}

$$a = \frac{\lambda}{2} = \frac{c}{2f_{pass}\sqrt{\epsilon_a}}$$

3. The **cell size A and B** are chosen to locate the first minimum in transmission spectrum at f_{stop} (when higher order modes can propagate)

$$A = B = \frac{c}{f_{stop}(\sqrt{\epsilon_r} + \sin \vartheta \sin \varphi)}$$

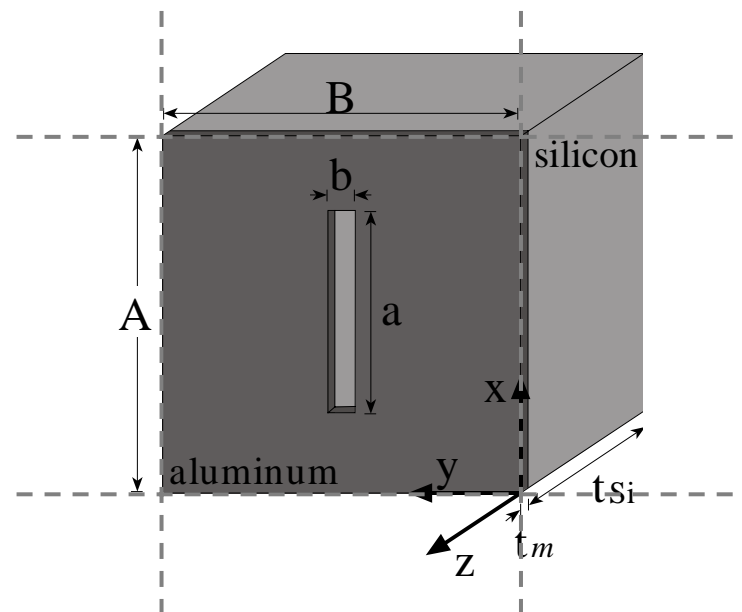
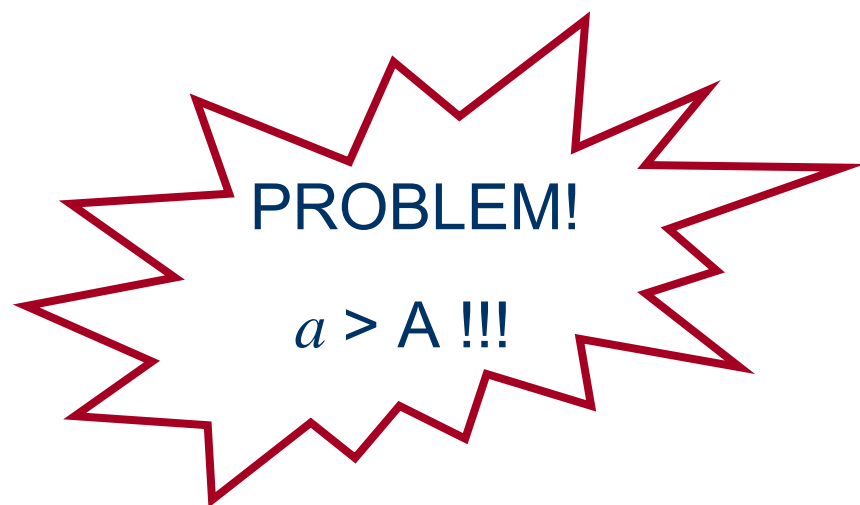
CHOICE OF PARAMETER VALUES



This FSS should have $f_{\text{pass}}=300$ GHz and $f_{\text{stop}}=450$ GHz.

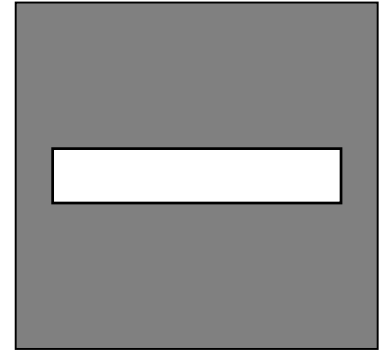
From analytical formulas, the tentative values result:

- substrate thickness $t_{\text{Si}}=289.7$ μm (available $t_{\text{Si}}=302$ μm)
- slot length $a=197$ μm
- cell size $A=B=176$ μm



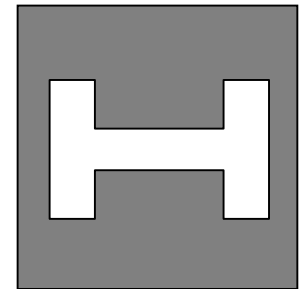
SLOT APPROACH

- enlargement of unit cell
- stop-band does not coincide with first minimum of frequency spectrum



DOGBONE APPROACH

- smaller length of dogbone aperture
- allows stop-band to coincide with first minimum of frequency spectrum



Both slot and dogbone structures have been optimized by using a **full-wave analysis code**, based on the **MoM/BI-RME** method.

PROTOTYPES OF FSS AT 300 GHZ

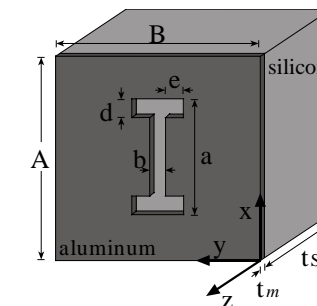
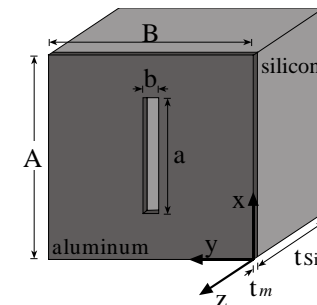


Different prototypes have been fabricated:

SLOT

Filter	a [μm]	b [μm]	d [μm]	e [μm]	$A = B$ [μm]	f_{pass} [GHz]
3S1	183.6	30.0	—	—	236.0	293
3S2	175.0	30.0	—	—	236.0	300
3S3	166.5	30.0	—	—	236.0	307
3D1	147.0	20.0	20.0	20.0	176.0	293
3D2	141.0	20.0	20.0	20.0	176.0	300
3D3	134.2	20.0	20.0	20.0	176.0	307

DOGBONE

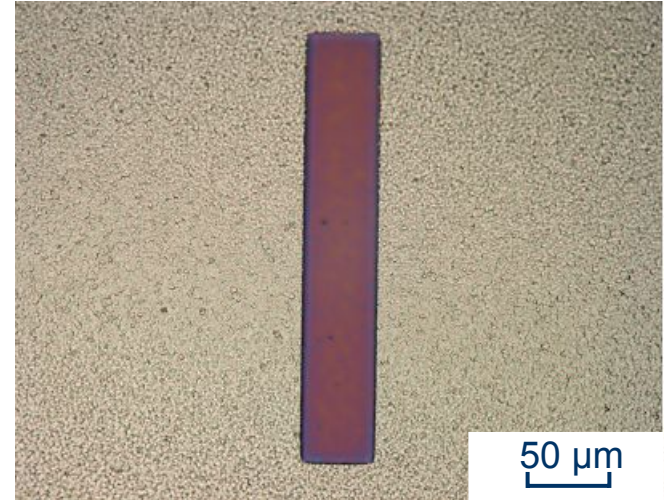
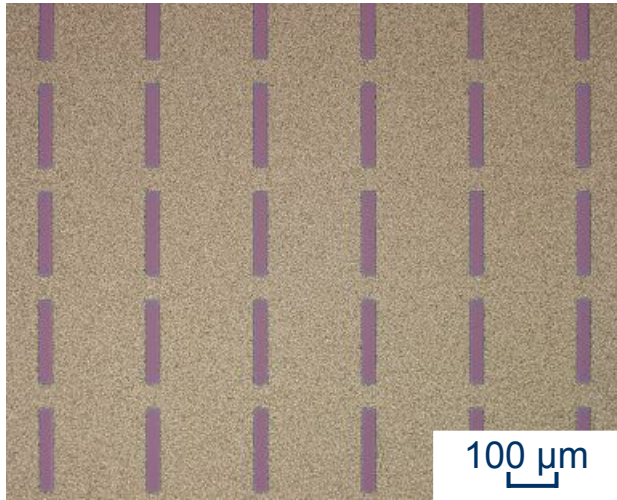


PROTOTYPES OF FSS AT 300 GHZ

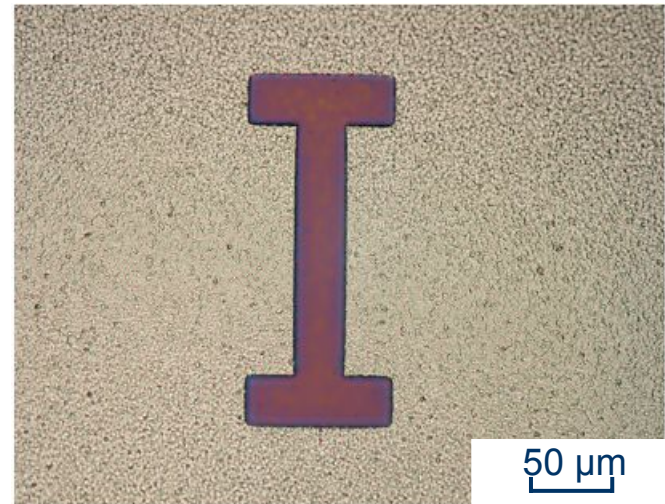
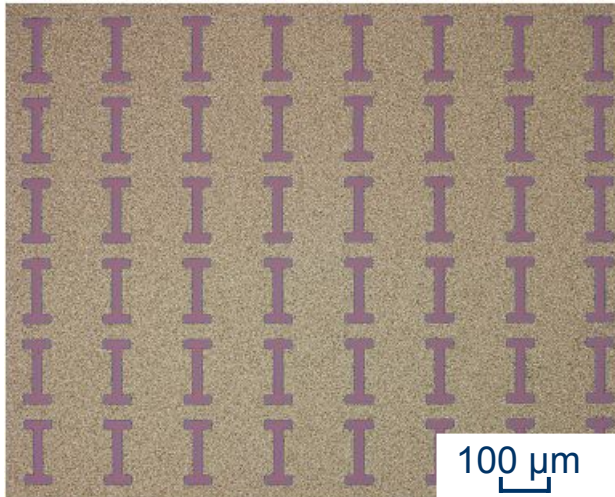


Aluminum was structured on a silicon wafer.

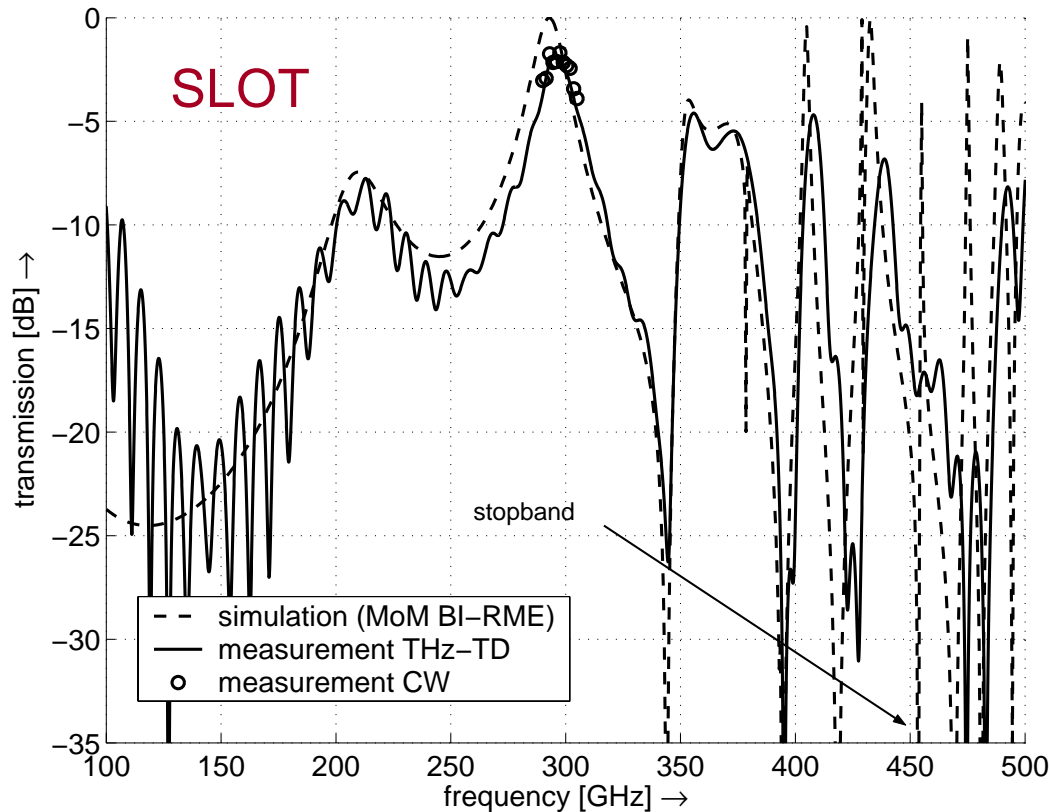
SLOT



DOGBONE

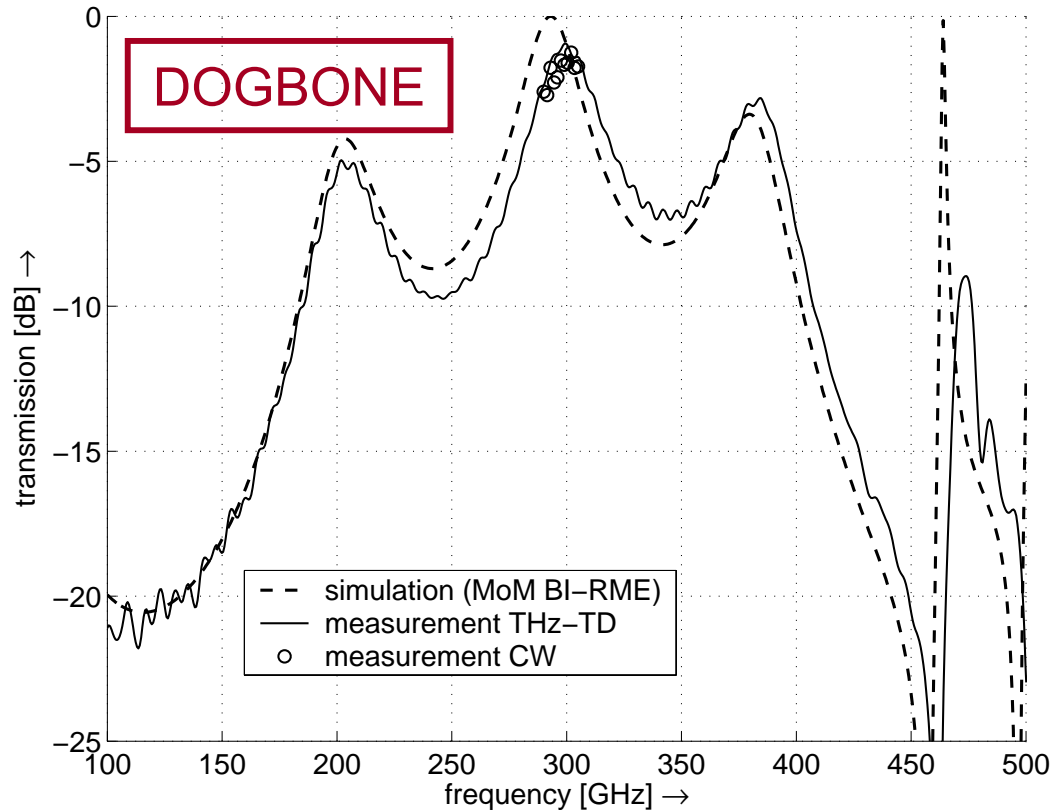


THz-TD spectroscopy & CW measurements were performed.



There is a **systematic frequency shift** of about 2%.
Insertion loss 1.6 dB - Stopband attenuation **only** 17 dB.

THz-TD spectroscopy & CW measurements were performed.



There is a systematic frequency shift of about 2%.

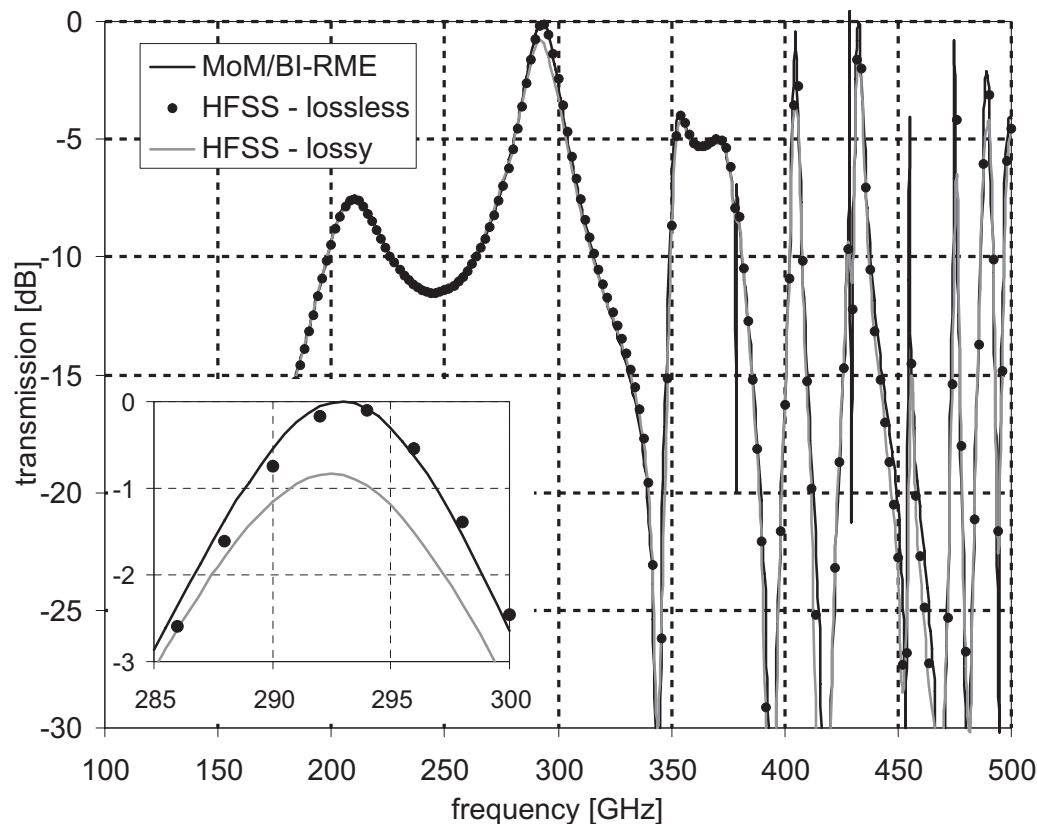
Insertion loss 1.0 dB.

Stopband attenuation >20 dB (447-463 GHz).



EFFECT OF LOSSES

The effect of losses has been studied by using HFSS 10, in the case of filter 3S1 (slot).



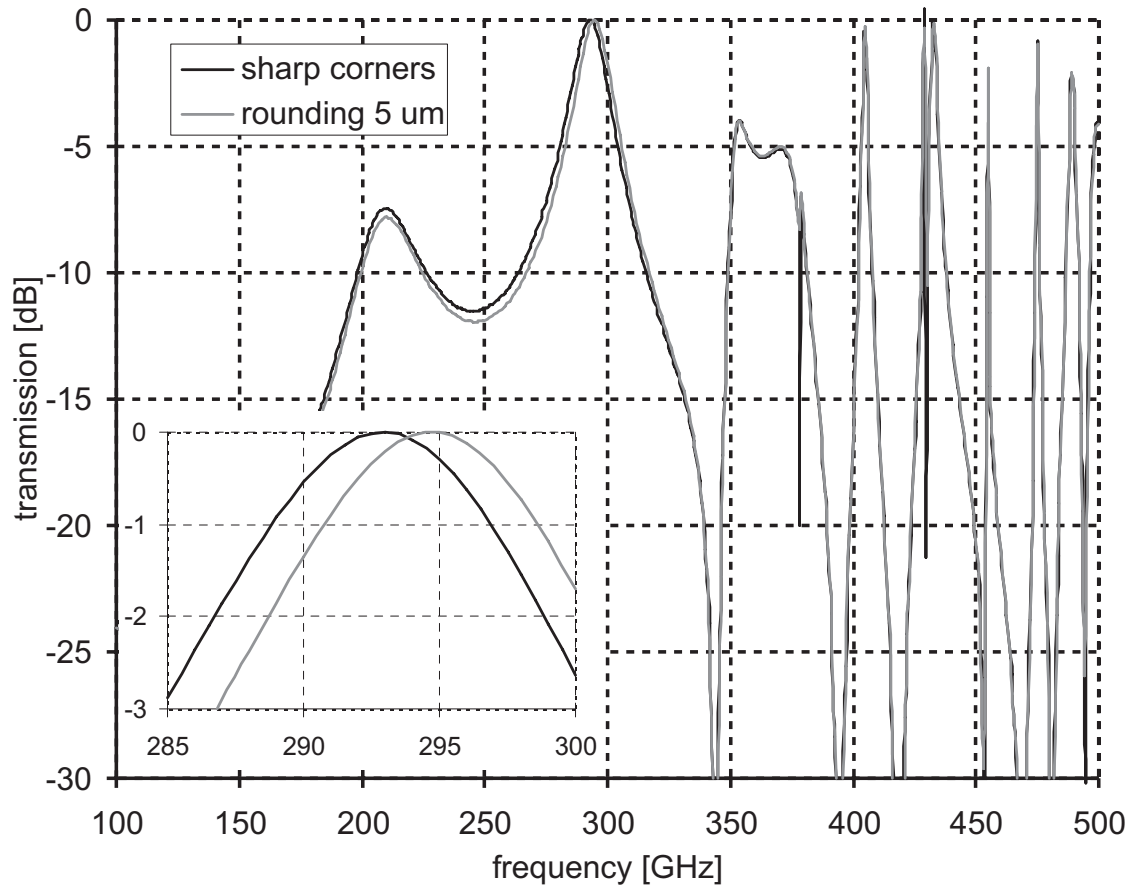
Ohmic losses ($\sigma=3 \cdot 10^7$ S/m): **0.8 dB** at 300 GHz

Dielectric losses ($\tan \delta=10^{-3}$): **0.15 dB** at 300 GHz



EFFECT OF ROUNDED CORNERS

The effect of rounding of the inner corners has been studied by using the MoM/BI-RME code, in the case of filter 3S1.



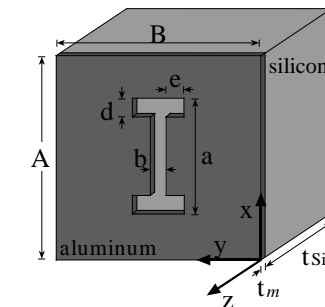
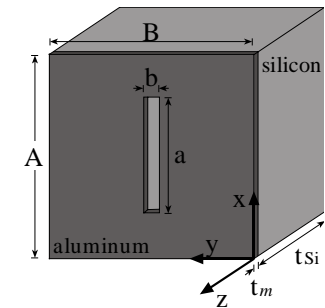
PROTOTYPES OF FSS AT 600 GHZ



The same design procedure has been adopted:

SLOT

Filter	a [μm]	b [μm]	d [μm]	e [μm]	$A = B$ [μm]	f_{pass} [GHz]
6S1	94.5	20.0	—	—	106.0	586
6S2	89.5	20.0	—	—	106.0	600
6S3	84.0	20.0	—	—	106.0	614
DOGBONE	6D1	71.0	12.0	12.0	106.0	586
	6D2	66.5	12.0	12.0	106.0	600
	6D3	62.2	12.0	12.0	106.0	614

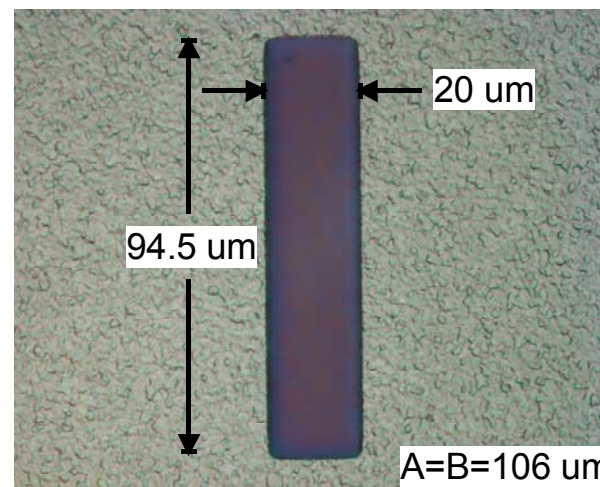
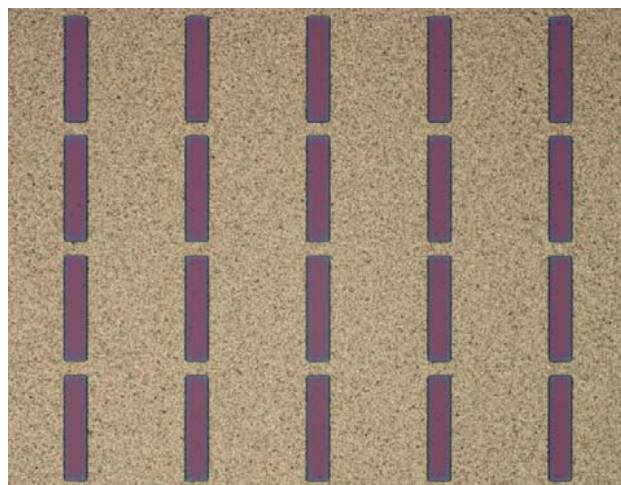


PROTOTYPES OF FSS AT 600 GHZ

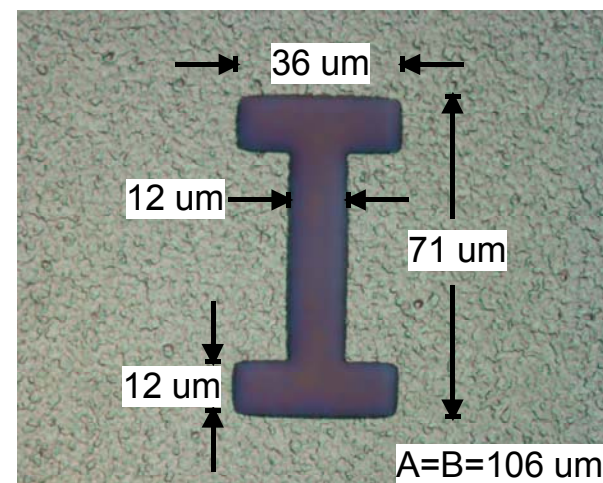
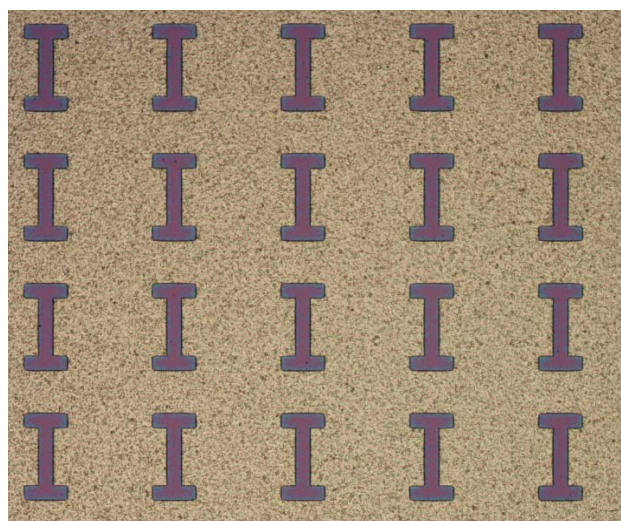


Aluminum was structured on a silicon wafer.

SLOT



DOGBONE



THz-TD spectroscopy & CW measurements were performed.

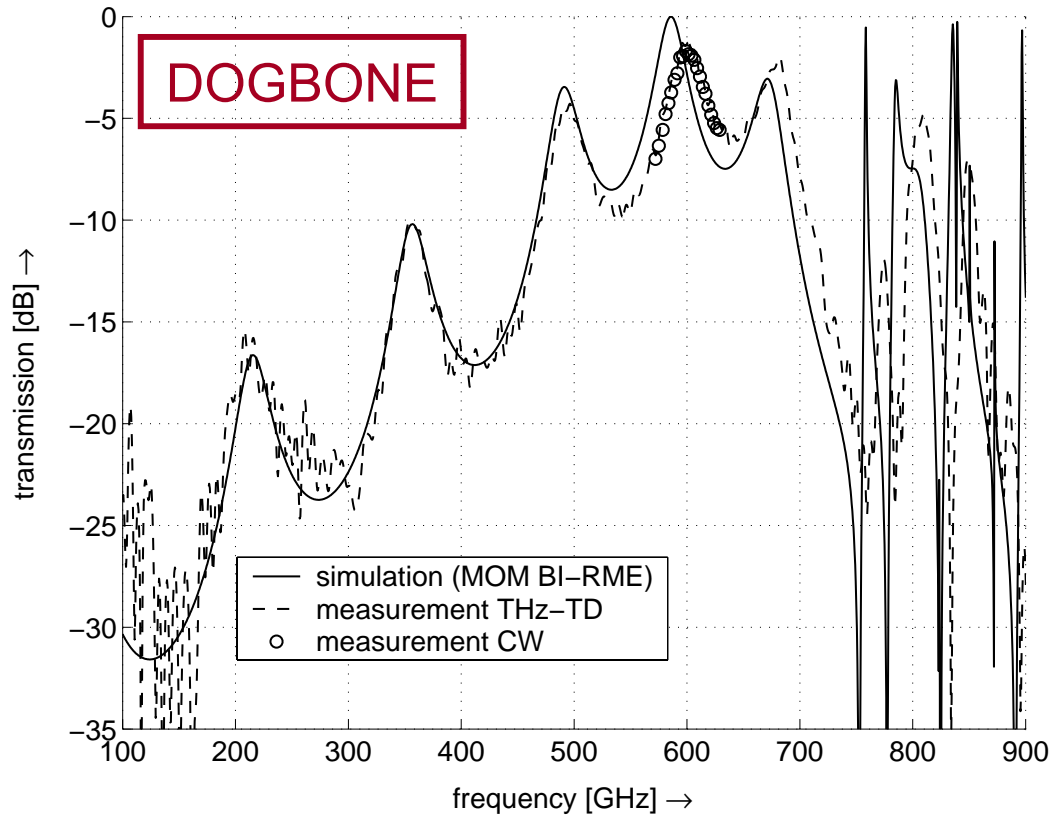


There is a systematic frequency shift of about 2%.

Insertion loss 1.4 dB.

Stopband attenuation >20 dB (752-760 GHz).

THz-TD spectroscopy & CW measurements were performed.



There is a systematic frequency shift of about 2%.

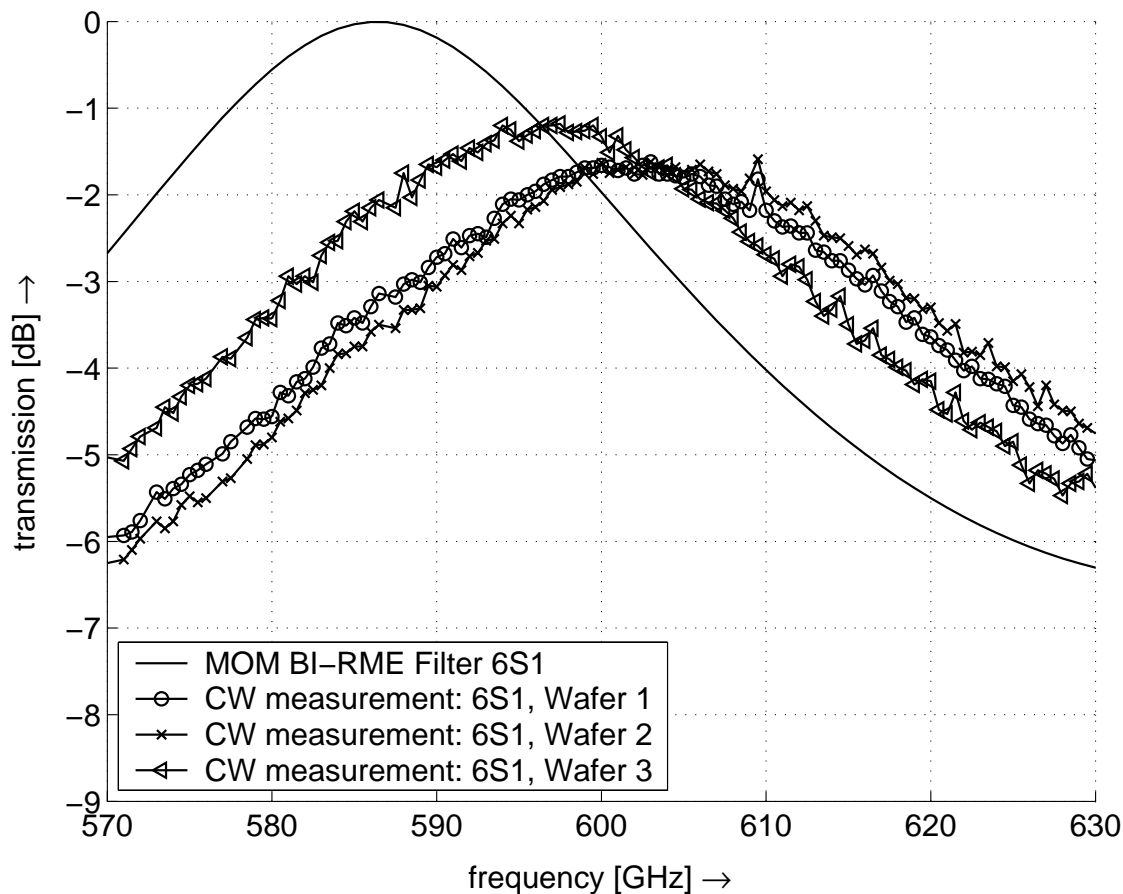
Insertion loss 1.6 dB.

Stopband attenuation >20 dB (760-768 GHz).



REPRODUCIBILITY

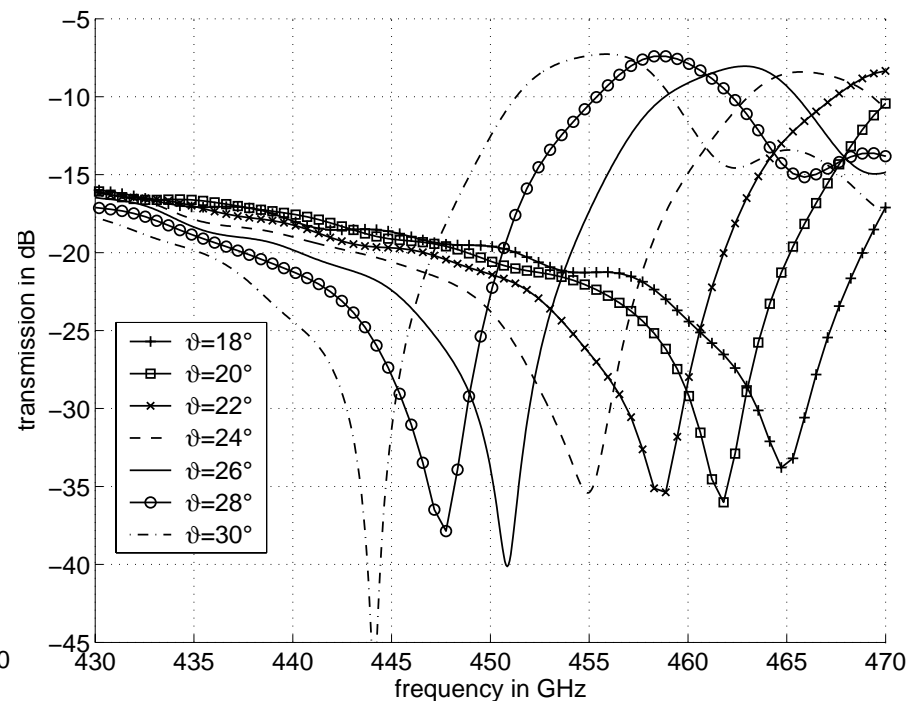
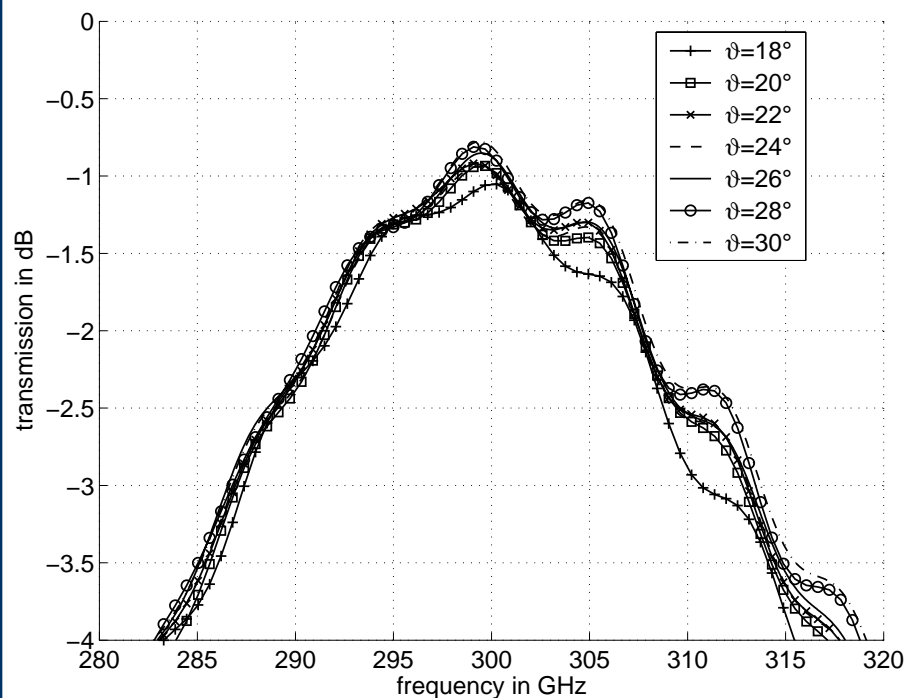
The reproducibility of the fabrication have been examined by comparing 3 identical filters coming from different wafers





FINE TUNING OF f_{STOP}

The stop-band frequency can be fine tuned by changing the angle of incidence. The pass-band remains unchanged



CONCLUSIONS



- ✓ Quasi-optical filters for suppressing undesired harmonics in frequency multipliers.
- ✓ Perforated metal screen on thick dielectric substrate: mechanically stable, standard technology.
- ✓ Filters at 300 GHz and at 600 GHz were fabricated and tested.
- ✓ HFSS was used to validate the simulation results and to evaluate the effect of ohmic losses
- ✓ Fine tuning of the stopband frequency by changing the incidence angle.



REFERENCES

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- S. Biber, M. Bozzi, O. Guenther, L. Perregrini, and L.-P. Schmidt, “Low-Loss Frequency Selective Surfaces on Thick Silicon Substrates for Sub-millimeter Wave Applications,” *2005 IEEE AP-S International Symposium*, Washington, DC, USA, July 3-8, 2005.